

Extragalactic Star Clusters
IAU Symposium Series, Vol. 207, 2001
Eva K. Grebel, Doug Geisler, and Dante Minniti, eds.

Triggering the Formation of Young Clusters

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Abstract. Star formation is triggered in essentially three ways: (1) the pressures from existing stars collect and squeeze nearby dense gas into gravitationally unstable configurations, (2) random compression from supersonic turbulence makes new clouds and clumps, some of which are gravitationally unstable, and (3) gravitational instabilities in large parts of a galaxy disk make giant new clouds and spiral arms that fragment by the other two processes into a hierarchy of smaller star-forming pieces. Examples of each process are given. Most dense clusters in the solar neighborhood were triggered by external stellar pressures. Most clusters and young stars on larger scales are organized into hierarchical patterns with an age-size correlation, suggestive of turbulence. Beads-on-a-string of star formation in spiral arms and resonance rings indicate gravitational instabilities. The turbulence model explains the mass spectrum of clusters, the correlation between the fraction of star formation in the form of clusters and the star formation rate, found by Larsen & Richtler, and the correlation between the size of the largest cluster and the number of clusters in a galaxy.

to appear in "IAU Symp. 207 on Extragalactic Star Clusters," eds. E. Grebel, D. Geisler, & D. Minniti, ASP Conference series, 2001, in press (held in Pucon Chile, March 12-16, 2001).

1. Introduction

Star formation may be triggered in a variety of ways. This review concentrates on three mechanisms: (1) sequential, in which pressures from one generation of stars move and compress the surrounding gas, causing another generation of stars to form, (2) turbulent, in which random and chaotic supersonic flows converge and diverge, bringing the gas into dense regions that last for about a crossing time, and (3) self-gravitational, in which density perturbations grow as a result of gravitational forces. Other compressive instabilities may contribute to the gravitational instability to drive star formation, such as the thermal or Parker instabilities. Cloud collisions are included in (2) and (3), considering that most clouds are part of a pervasive fractal network that is probably generated by turbulence and self-gravity. Density wave triggering is included in (3) if the waves induce local gravitational instabilities, forming the characteristic beads-on-a-string pattern of giant cloud complexes in spiral arms.

These processes trigger both individual stars and whole star clusters, the difference being a matter of scale for the self-gravitating cloud that forms. If a cloud is big enough, then smaller versions of the same three processes can trigger smaller clouds inside of it, eventually getting down to the scale of individual stars. For example, the dust lane in a spiral arm may be gravitationally unstable to make $10^7 M_\odot$ cloud complexes. These complexes will be born with a lot of turbulent energy, from both the pre-cloud gas and the binding energy, and the turbulence will randomly compress the gas inside, making smaller clouds. If some of these clouds form stars, then the pressures caused by these stars can trigger more star formation inside other turbulence-compressed clouds. Thus all three processes can happen simultaneously in the same region, sometimes in a nested fashion and sometimes in juxtaposition. The point of this classification of processes is not to suggest that star formation follows only one of three possible paths, but to distinguish between the various morphologies of clustering that we see in young stellar regions.

Many young clusters are embedded in dense gas clumps that are at the interface between a molecular cloud and a high-pressure source, such as an HII region. These clusters were probably triggered by the HII region as it expanded into the cloud and are examples of the first process. When the same clusters are viewed from a greater distance, they are often found to be part of a fractal hierarchy of many other clusters, including slightly older OB associations and even older star complexes. This hierarchical pattern and a corresponding correlation between age and size has the same form as in a compressibly turbulent fluid, in which case the turbulent nature of cluster triggering becomes evident on the larger scale. It might also be true that all of this region is one of the beads in a galactic spiral arm, or perhaps it is a flocculent spiral arm by itself. We know that gaseous self-gravity is important on these large scales, so the whole process will appear to have begun with an instability that led to a cascade of interconnected events. What is the actual process of cluster formation in a case like this (which resembles Gould's Belt)? Is it (1), (2), or (3) in the list above? The individual clusters resulted from a combination of processes. Yet the distinct morphologies of where and when they formed help us to understand which process dominates on which scale.

In the following sections, observations of these three processes are reviewed. A more comprehensive review of the sequential process is in Elmegreen (1998). Other reviews of star formation are in Evans (1999) and in the conference proceedings for Protostars and Planets IV (Univ. Arizona Press, 2000).

2. Sequentially Triggered Star Formation

There are many examples in the recent literature where clusters appear to have been triggered by nearby high-pressure events. Lefloch & Chernicharo (2000) found 12 μ cores that are probably protostars inside dense clumps that are seen in 1.3 mm at the edge of the Trifid Nebula. They derived an expansion age of the HII region to be 0.35 My, and a preshock density $2 \times 10^3 \text{ cm}^{-3}$. The instability time, $0.25 (G\rho)^{-1/2} \approx 0.35 \text{ My}$ (Elmegreen 1989a), agrees with the expansion age, suggesting triggering. A similar configuration with an embedded cluster next to the Rosette nebula was discussed by Phelps & Lada (1997).

Lada et al. (1991) found two dense embedded clusters in the Orion molecular cloud at the locations of the densest cloud cores. These cores are the heads of giant cometary clouds, pointing toward and probably formed by the expansion of the Orion nebula (Bally et al. 1987). The head of the southern core is a thin cloud running parallel to the ionization front (Dutrey, et al. 1991) that is probably compressed gas. Many young stars and protostars are lined up along this strip (Reipurth, Rodriguez & Chini 1999). Images from 2MASS of the whole region are in Carpenter (2000).

An IRAS image of the embedded cluster near rho Ophiuchus makes it look like a comet head too (IPAC image from <http://www.ipac.caltech.edu>). The source of pressure is in the northwest. This is the triggering configuration proposed by de Geus (1992) who attributed the compression to shocks from the Upper Sco OB association. Shocks from the Cen-Lupus association probably triggered Upper Sco in a previous step (Preibisch & Zinnecker 1999). Another giant shell containing several young clusters surrounds the HII region and bubble source W5, as seen in IRAS 15 μ and 25 μ maps (Kerton & Martin 2000).

One of the first examples of sequential star formation, found by Sancisi et al. (1974), includes the Per OB2 association and its two clusters, IC 348 and NGC 1333. Sancisi et al. pointed out that this association lies in an OH+HI shell with a peculiar velocity, and they suggested that the clusters were triggered by the shell's expansion. CO maps of the Perseus region by Sargent (1979) found other age sequences inside the association. The embedded clusters are not very dense (Lada & Lada 1995; Lada, Alves, & Lada 1996), but the region is older than Orion (Palla & Stahler 1999, 2000) and the pressures are not as large. Now the whole region can be seen with 2MASS (Carpenter 2000).

There are many other embedded clusters in the solar neighborhood. Most of them look triggered because of their proximity to high pressure sources (see the table of sources and discussion in Elmegreen et al. 2000). Clusters whose formation is not so clear tend to be older, so their pressure sources could have decayed. The partially embedded cluster IC 5146 is an example (Lada, Alves, & Lada 1999). It has no obvious source of high pressure nearby, but it is at the tip of an elongated cloud that makes it look triggered anyway.

Supernovae can trigger star formation, but most catalogued supernova remnants are too young to have started this process yet. A recent example of supernova triggering seems to be G349.7+0.2, which has 3 IRAS sources along the perimeter of a supernova shell (Reynoso & Magnum 2001). Other shells have triggered star formation on their periphery (Xie & Goldsmith 1994; Yamaguchi et al. 2001), but these shells are probably older than single supernova remnants and result from a combination of supernova and stellar wind pressures in an aging OB association (McCray & Kafatos 1987).

Giant shells in other galaxies are often seen with triggered star formation along their peripheries (Brinks & Bajaja 1986; Puche et al. 1992; Wilcots & Miller 1998; Steward et al. 2000; Stewart & Walter 2000). IC 2574 (Walter & Brinks 1999; Steward & Walter 2000) has an example where HII regions on a shell contain clusters ~ 3 My old, and another cluster 11 My old is in the center.

What are the characteristics of sequentially triggered star formation? To be reasonably sure that such triggering happened, we need two distinct regions of star formation observable as either stars or IR clusters with a separation and

age difference that has a ratio equal to a reasonable propagation speed. The age difference should also be several tenths of the ambient gas dynamical time, $(G\rho_0)^{-1/2}$, for density ρ_0 near the younger cluster. Between the two clusters, there should be a region with a low density where the gas was cleared away by the pressure disturbance from the older cluster. The clusters should also be young enough that neither has had time to move very far from its point of origin.

Observations of star formation within the nearest several kiloparsecs suggest that most of it occurred in dense clusters, and that most of these clusters were triggered by previous generations of stars. Further from the Sun, such triggering will be harder to see unless there is an obvious shell. This is because most triggering inside OB associations has a short length scale, perhaps 1 to 10 pc, and external galaxies are too far away to resolve this scale. Also, shells tend to shear away quickly and high pressures last only a relatively short time, so it will be unusual to catch a triggering event in the act. Most clusters also disperse rather quickly. Only 10% of young local stars are in clusters, even though most stars probably formed this way, and this suggests that most newborn clusters lose their stars quickly. A triggering act has to be confirmed while the stars are still in their clusters so we can be sure where they formed.

3. Turbulence Triggering

Supersonic turbulence compresses gas in random places, making transient clouds that last for about an internal crossing time once they form – longer if we consider also their formation time, which is the flow time in the external medium (Elmegreen 1993). Numerical simulations show this process well (Vázquez-Semadeni, Passot, & Pouquet 1996; Ballesteros-Paredes, Vázquez-Semadeni, & Scalo 1999; Klessen, Heitsch, & Mac Low 2000; Padoan et al. 2001).

A characteristic of turbulence triggering is that clusters are born in hierarchical and fractal patterns on both galactic scales (Elmegreen & Elmegreen 2001) and local scales. T Tauri stars in the local field are hierarchically distributed (Gomez, et al. 1993), and the embedded stars in clusters can be hierarchical too (Elmegreen 2000; Testi et al. 2000). Hierarchical structure is probably the result of the scaling between velocity and separation for a turbulent fluid: large scales have large relative velocities, making large compressed sub-regions, and small scales have small relative velocities, making small compressed sub-regions.

Interstellar turbulence is pervasive, although not all regions are turbulent and not all structures are fractal. Non-fractal structures include expanding shells, two-arm density wave modes, relaxed clusters, cometary clouds and Bok globules. Fractal structures include diffuse clouds, flocculent spiral arms, young clusters where the stars have not moved much from their birth, and the interiors of many weakly self-gravitating clouds. When directed pressures shape a cloud, shell or spiral arm, the overall morphology is determined by those pressures, but when turbulence is free to define a structure independent of rigid boundaries, fractal patterns appear.

Turbulence can be generated by expansion or other directed pressures as the moving gas mixes with the environment and undergoes Rayleigh-Taylor and Kelvin-Helmholtz instabilities. Self-gravity can make turbulence as gas collapses locally and mixes. It can also be generated by Parker (1965) instabilities (Asseo

et al. 1978) and Balbus-Hawley (1991) instabilities (Sellwood & Balbus 1999) which involve magnetic mixing. Turbulence decays rapidly (Stone, Ostriker, & Gammie 1998; MacLow, et al. 1998), but in a self-gravitating medium, there is always a source for more turbulence as the region contracts.

Star formation in a turbulent medium should have several special characteristics. First, the star-forming clouds should be randomly placed in part of an overall fractal gas distribution. This fractal gas will have a scale-free power spectrum (Crovisier & Dickey 1983; Green 1993; Lazarian & Pogosyan 2000; Stützki et al. 1998; Stanimirovic et al. 1999; Westpfahl et al. 1999; Elmegreen, Kim, & Staveley-Smith 2001). The young stars that form in these clouds should have the same fractal pattern as the gas at the time of their birth. Their birth times could be random, although there could be some fractal substructure in their birth times too. The clouds and clumps in a fractal gas should also be clustered together. As a result, most stars should be born in clusters of other stars (Elmegreen et al. 2000). These clusters will then have a mass spectrum close to $n(M)dM \propto M^{-2}dM$ because hierarchical structure has equal total mass in equal intervals of log mass. Fractal structure that is clipped to give only fractal islands has the same mass spectrum for those islands (Elmegreen 2001). Fractal star fields should also be correlated with respect to age and distance. Larger regions will have longer durations of star formation with a duration-size relation similar to the crossing-time-size relation for interstellar turbulence (Efremov & Elmegreen 1998; Battinelli & Efremov 1999; Harris & Zaritsky 1999). Models of this duration-size relation are in Scalo & Chappell (1999) and Nomura & Kamaya (2001). Evidence for short star formation times in small regions is in Ballesteros-Paredes, Hartmann, & Vazquez-Semadeni (1999) and Elmegreen (2000).

The turbulence model of star formation is important for clusters because it offers the most natural explanation for the cluster mass spectrum (Elmegreen & Efremov 1997), which is observed to be close to $M^{-2}dM$ for local clusters (Battinelli et al. 1994) and OB associations, as seen by the distribution of HII region luminosities (Kennicutt, Edgar, & Hodge 1989; Comeron & Torra 1996; Rozas, Beckman & Knapen 1996; Feinstein 1997; McKee & Williams 1997; Oey & Clarke 1998).

The $\sim M^{-2}dM$ power law also appears at the high mass end of the globular cluster luminosity function (Ashman, Conti, & Zepf 1995), and for super-star clusters in starburst regions (Whitmore & Schweizer 1995; Zhang & Fall 1999).

The turbulence model explains the correlation between the number of clusters and the mass of the largest cluster (Whitmore 2000) as a size of sample effect in a random cluster formation model. Similarly, it explains the correlation between the star formation rate and the relative fraction of star formation that occurs in the form of clusters (Larsen & Richtler 2000). These are both statistical properties for an ensemble where the clusters form in virialized clouds in a medium with a uniform average total pressure (total pressure considers the sum of the ram pressure from flows and the thermal pressure in the compressed regions). The derivation for the Larsen & Richtler correlation goes like this:

For a general interstellar disk, the total pressure scales with the product of the gas mass column density and the total mass column density of all the material, including stars, dark matter, and gas, that lies inside the gas layer

(Elmegreen 1989b). For an interstellar medium that is close to the threshold for instability, the gas mass column density is roughly proportional to the total. Thus the pressure scales approximately as the square of the gas mass column density in a critical ISM:

$$P_{ISM} \propto \Sigma_{gas}^2. \quad (1)$$

The star formation rate scales with this gas column density approximately as $SFR \propto \Sigma_{gas}^{1.4}$ (Kennicutt 1998), presumably as a result of the conversion of the available gas (one power of Σ) into stars on a dynamical time scale (the extra fractional power of Σ). These two equations give

$$P_{ISM} \propto SFR^{1.4}. \quad (2)$$

For clusters, the virial theorem, $c^2 \sim 0.2GM/R$, and the internal pressure, $P_{int} \sim 0.1GM^2/R^4$ give a relation between mass and pressure,

$$M \sim 6 \times 10^3 M_{\odot} \left(P_{int}/10^8 \text{ K cm}^{-3} \right)^{3/2} \left(n/10^5 \text{ cm}^{-3} \right)^{-2}. \quad (3)$$

The normalization for this relation comes from the properties of the molecular core near the Trapezium cluster in Orion (Lada, Evans & Falgarone 1997). From this we get $M \propto P_{int}^{3/2}$ for internal pressure P_{int} , which is generally larger than the environmental pressure, P_{ISM} , but proportional to it on average; thus $M \propto P_{ISM}^{3/2}$. This last step, setting $P_{int} \propto P_{ISM}$, is more of an assumption than an observation, but it seems reasonable for an ensemble average. The above equations can now be combined to give $M \propto SFR^2$.

Now it is important to realize from the fractal model that this mass is the largest mass than can form, on average, in a virialized cloud at the ambient pressure. Smaller mass clusters form as part of the hierarchy of structures on smaller scales. Larger clusters cannot form systematically because they will be over-pressured. Of course, larger mass clusters can form in statistical fluctuations of the local pressure, but the present discussion concerns only the average properties of clusters. For this reason, we write explicitly $M_{max} \propto SFR^2$ to remind us that this is a maximum cluster mass.

The total star formation mass in the form of young dense clusters equals the integral of the cluster mass weighted by the cluster mass spectrum over the mass interval ranging from some smallest mass, M_{min} , up to the maximum cluster mass, M_{max} . For an $n(M)dM = n_0 M^{-2}dM$ mass spectrum, we first integrate from M_{max} to infinity to give the normalization factor n_0 , i.e. $\int_{M_{max}}^{\infty} n_0 M^{-2}dM = 1$, or $n_0 = M_{max}$. Then $n(M)dM = M_{max} M^{-2}dM$. With this normalization, the total mass is $M_{tot} \propto M_{max} \ln(M_{max}/M_{min})$, which depends only weakly on M_{min} . Considering only the first term, which is the most strongly varying, we get $M_{tot} \propto M_{max} \propto SFR^2$. From this, the fraction of the star formation in the form of dense clusters, M_{tot}/SFR , scales directly with the star formation rate:

$$M_{tot}/SFR \propto SFR \quad (4)$$

This is essentially the relation found by Larsen & Richtler (2000). In addition, an intermediate step in this derivation, not shown here, gives $M_{max} \propto$ the number of clusters, which is the correlation found by Whitmore (2000).

We see from this discussion how easily the turbulence model explains the mass function of clusters and the correlations between maximum cluster mass, star formation rate, pressure, and total number of clusters. This means that turbulence alone explains why starburst regions have more, bigger, and denser clusters. It may also explain how the high pressure environment in the early Universe (e.g., in the turbulent proto-halo) led to the formation of globular clusters. It does not explain the Gaussian distribution for globular cluster magnitudes, however, which may be a problem for the model if low mass cluster destruction is so sensitive to local environment that the theoretical peak of the evolved Gaussian cluster luminosity function is more variable with environment than the observed peak (e.g., Vesperini, this conference, but also see Fall, this conference).

4. Gravitational Instability Model

Gravitational instabilities may drive random structure in interstellar gas, as shown by spiral chaos models (Toomre & Kalnjas 1991; Huber & Pfenniger 1999; Semelin & Combes 2000) and in the simulations by Wada & Norman (1999, 2001) and Wada, Spaans, & Kim (2000). In these models, gravity makes scale-free structures because of non-linear interactions between the primary structures that form at the Jeans length. The Jeans length is about equal to the scale height, but neither is well defined in a turbulent medium.

Gravitational instabilities are easier to see when they occur in spiral arms and resonance rings. The identification of giant spiral arm cloud and star-forming complexes as the result of gravitational instabilities has been made in a series of papers, beginning with Elmegreen (1979) and including Viallefond, Goss & Allen (1982), Nakano et al. (1987), Grabelsky et al. (1987), Elmegreen & Elmegreen (1983, 1987), Lada et al. (1988), Ohta, et al. (1988), Boulanger & Viallefond (1992), Tilanus & Allen (1993), Rand (1993a,b), Garcia-Burillo, Guélin & Chernicharo (1993), and Kuno et al. (1995). The identification of giant star-forming regions in ILR rings as the result of gravitational instabilities was made by Elmegreen (1994), D. Elmegreen, et al. (1999) and Buta, Crocker, & Byrd (1999). Similar complexes in an outer resonance ring were found in NGC 1300 (Elmegreen et al. 1996). In the case of ILR rings, there are also super star clusters (Maoz et al. 1996), perhaps for the reasons given above: the total SFR is large so the clusters sample far out in their mass function.

Gravitational instabilities have also shown up in interacting systems. The merger galaxy NGC 6090 has most of its interstellar medium between the two nuclei and at very high column density, around $10^{3.5} \text{ M}_{\odot} \text{ pc}^{-2}$ (Mazzarella & Boroson 1993; Bryant & Scoville 1999; Dinshaw et al. 1999). This gives the average interstellar pressure a value of $\sim 10^8 \text{ K cm}^{-3}$, which is four orders of magnitude larger than the local interstellar pressure. At this position, there is a chain of four, regularly-spaced, young massive star clusters along a spiral arm. Their morphology is like the familiar beads-on-a-string pattern in disk spiral arms (Kuno et al. 1995), but in this case in an extreme environment.

Other examples might be the unusual supermassive clusters in NGC 253 (Watson et al. 1996; Keto et al. 1999) and NGC 5253 (Turner, Beck & Ho (2000)). They are by far the largest clusters in these galaxies. They are located

near the galaxy centers and are not part of any obvious fractal pattern or sequential triggering event. They are also not part of a similar chain of clusters, so they do not look like a beading instability as do complexes in spiral arms or ILR rings. Nevertheless, they probably formed by gravitational instabilities in the inner disks of these galaxies.

5. Summary

Most stars form in clusters and most clusters in the solar neighborhood formed as a result of direct and sequential triggering stimulated by other clusters. When viewed from a distance, clusters can have a fractal and time-correlated pattern suggestive of turbulence. Presumably ISM turbulence sets up the fractal pattern independent of star formation, and then star formation inside this pattern operates locally by a variety of methods, preserving the overall pattern. Gravitational instabilities also operate in the turbulent medium, inside sequentially triggered clouds, and in larger-scale environments organized by systematic flows. The most obvious evidence for such organized patterns comes from spiral arms and resonance rings, where a confinement in two dimensions leads to the formation of regularly spaced ring hotspots and spiral arm beads on a string.

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